eXoft, Innovative Soft-Rigid Exoskeleton for Smart Factory

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Luca Carbonari, Ilaria Palomba, Massimiliano Solazzi, and Carmen Visconte

Abstract Work related musculo-skeletal disorders represent a relevant percentage of occupational diseases in developed countries. Aside the laborers discomfort, they also reflect on companies with relevant economic effects. Nonetheless, the spread of exoskeletons for industrial applications is still limited. The reasons are to be sought on how they are perceived by workers: for many of them, their reduced mobility and not perfect adaptability to the kinematics of the human body make them more of a nuisance than a real help. The spread of wearable devices in industrial scenarios could bring advantages not only to jobs ergonomics and injuries assessment, but also to safety and risk management. The exoskeletons worn by labourers can be conceived as tools able to share quantitative data about the user posture and position within the working environment for active safety strategies and machines command. The object of the eXoft project is an active exoskeleton with innovative mechanical and actuation designs, conceived for integration in collaborative robotics environment. The purpose is to improve the comfort and safety of labourers tasked with heavy or repetitive jobs, while providing a tool for a safer integration of human-in-the-loop workflows.

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1 Introduction

Exoskeletons (ESs) are Wearable Devices (WDs) aimed at helping people making un-ergonomic or repetitive movements by exerting a supporting action on certain body parts (e.g., arms, shoulders, or back). Their use allows workers to make such movements for long time and ward-off the onset of Work Related Musculo-Skeletal Disorders (WRMSDs) [1]. For example, high discomfort and ergonomics problems that affect workers have been noted in automotive production lines [2]; some studies report that 70% of tasks carry a high risk of WRMSD for the neck, and 60% for the back [3]. Nonetheless, the spread of ESs is still limited by factors which are disconnected by their potential effectiveness. Authors of [4], for example, isolated five families of factors (physiological, work-related, policy-related, psycho-social and implementation-related), acknowledging that the workers' reluctance reduces if a substantial efficiency improvement is introduced. Also, they claim that the implementation strategy is of importance to convince employees to use an ES at work, for it is a dragging theme for enhancement of perceived usefulness.

For this reason, the integration of WDs in the production workflow is crucial, and in fact is the subject of recent investigations. Karvouniari et al. [5] developed a methodology for designing the integration of ESs in manufacturing lines using virtual reality: the approach was oriented at the optimization of the ES and at the training of its user. Other works conceived the ES as a Cyber-Physical System (CPS): Bances et al. [6] envisioned ES as an entity in intensive connection with the surrounding world and part of a network of interacting elements. Their IoT oriented vision particularly fits the Industry 4.0 (I4.0) paradigm [7], based on the interaction among CPSs. The implementation of smart ESs makes a further step on the guidelines of Industry 5.0 (I5.0) and its human-centric vision [8], since they can play an important role in the support of labourers tasked in Human In The Loop (HITL) operations, which are of great importance for the pursuing of I5.0 goals. Of course, the first non-human actors in the scene are collaborative robots (cobots), which represent a pillar for both I4.0 and I5.0 [9].

The integration of cobots (as in the example of Fig. 1) makes possible to advance from coexistence to collaboration between workers and machines [10]. For an effective Human Robot Collaboration (HRC) it is fundamental a correct information exchange between the parties, through suitable interfaces that monitor human behavior and strategies that increase the mutual awareness of the human-robot dyad [11]. Different commercial solutions have been proposed to sense human whole-body kinematics [see, e.g., Xsense (https://www.xsens.com)] as well as for accurate and wearable EMG acquisition (e.g. Trigno by Delsys, Inc. or FreeEMG by BTS Spa) and ground reaction forces (http://www.moticon.de). For warning feedback to humans on cobot status, WDs usually rely on vibrotactile stimuli, also applied for guidance and HRC [12]. Wearable haptic systems can also be an effective and unobtrusive solution to reproduce a wider range of haptic cues [13]. In each case, however, the importance of having a comfortable interface is well stressed for both ergonomic reasons, and technological acceptance.

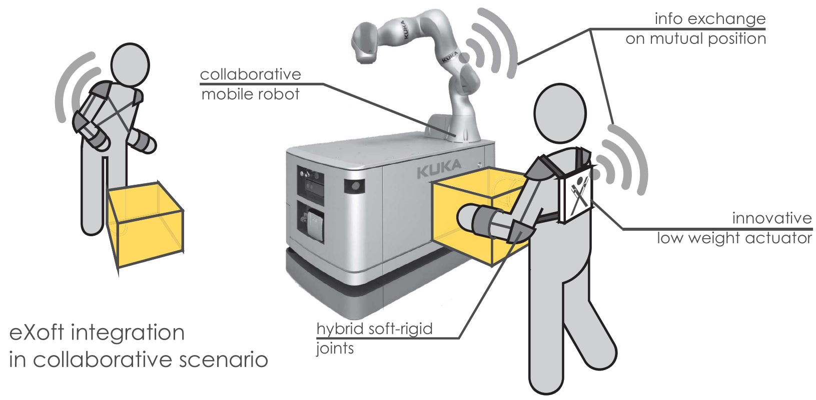

Fig. 1 Integration of the eXoft exoskeleton in collaborative environment

The focus of the eXoft project is an active ES with innovative mechanical and actuation designs, conceived for integration in collaborative robotics environment. The purpose is that of improving comfort and safety of workers. The literature shows that an actual impact on labourers' quality of work is possible, but for being effective a novel WD should also be well accepted: comfort, ease of use, and an actual efficiency enhancement seem to be necessary. A set of requirements of COMFORT / EFFECTIVENESS / INTEGRATION can be drawn:

- COMFORT. The comfort and ease of use are crucial points for obvious reasons. Many applications can be mentioned [14] highlighting the diversity of embodiments and hardware designs. However, their diversity also underscores a field immaturity which leaves room for further development, especially in the direction of hybrid soft-rigid structure which has been investigated mostly for non-industrial (rehabilitation and assistive) purposes [15].
- EFFECTIVENESS. A WD is more likely to be accepted if it brings a true enhancement of the user productivity. Active ESs are surely advantaged in this sense with respect to passive ones [16]. A lot has been done in this direction, although the researchers mainly focused on lower limbs (especially for development of innovative actuations and control algorithms [17]).
- INTEGRATION. To meet the requirements of I4.0 and I5.0 and being a real help for HRC development, the ES must be part of a wider network of cooperative tools. Despite the interest aroused by the topic (mentioned in several surveys [18]), only few applications can be found in the recent past [19].

2 Project Motivation

Despite their potential benefits, industrial exoskeletons did not find their way through the fabric of Small and Medium Enterprises (SMEs). The reluctance is mostly due to the poor usefulness perceived by the final users, i.e., the labourers who see them as an impediment to their mobility more than an actual help. This happens notwithstanding their beneficial effect, which has been documented widely in the recent past. Together with comfort, usefulness seems to be the one aspect to be refined to achieve the goal of a wider spread of exoskeletons. In fact, according to the state of the art in the field, the acceptance of wearable devices is more likely to increase if they yield a noticeable improvement to the efficiency of the worker, which is better perceived with active exoskeleton. The integration of the exoskeleton with the work environment is a relevant topic to be developed as well. Firstly, sharing information with other entities can actively improve the safety of the work-space: proximity with robots, current posture, and intensity of the effort the worker is making are examples of measurable data that a device worn by a labourer can collect.

With such premises, eXoft proposes an upper-limb exoskeleton having an innovative hybrid rigid soft structure capable of enhancing the comfort perception by the final user. Moreover, the device will be active to deliver a solid and well perceptible sense of effectiveness. The integration of the device with its environment will also introduce a further safety management chance, in addition to an additional human-robot interaction (HRC) interface.

3 The Work Team

Four research units (RUs) are involved in eXoft (UnivPM, SSSA, UniPD, PoliTO), all of them with solid scientific background on the main topics, very well-equipped scientific labs (with most part of the experimental rigs useful for the project development: rapid prototyping equipment, passive industrial exoskeleton for testing and comparison, collaborative robots for implementation), important international scientific collaborations in the field, and relevant industrial connections.

The eXoft team involves multi-disciplinary expertise ranging from design and testing of innovative exoskeletons (SSSA), optimization of deformable and vibrating structures (UniPD), design of innovative actuators (PoliTO), and industrial and collaborative robotics (UniPM).

All the researchers involved are strongly committed with merging their complementary expertise for improving exoskeletons spread in SMEs. The interaction between RUs will be maximum in the first part of the project. Then, each RU - according to its core skills- will lead the development of a different aspect of the object of the study. Finally, a prototype device will be tested in a use scenario where it will be challenged not only with its ability to ease the work of its user, but also with the interaction with a collaborative work-cell.

4 Objectives and Expected Results

The main objective of eXoft is to propose a technological option to industrial exoskeletons to enhance their acceptance among the labourers. The project will develop an active exoskeleton with innovative actuation and hybrid rigid-soft structure. The information collected while wearing the device will ease up its integration in a productive scenario with the purpose of contributing to the ergonomics of the work cell and of acting as an interface for Human Robot Interaction (HRI) for the development of Human In The Loop (HITL) applications. Such improvements will impact on the usability and effectiveness of the exoskeleton, promoting its use in industries. The goals will be reached by pursuing three objectives:

- COMFORT: the less the exoskeleton impacts on its user movements, the more it will be perceived as an actual help. Therefore, the device should be designed to provide the labourer with the physical help needed during un-ergonomic tasks while remaining as much as possible unsensed during downtimes. To this aim the project proposes a hybrid soft-rigid structure, optimized to be effective when necessary while compliant with users' motions.
- EFFECTIVENESS: to deliver an actual service to the wearer, the exoskeleton must be as much as possible efficient. To this aim, the project proposes an active device able to provide its user with the needed amount of force without having it formerly stored. Passive exoskeletons, in fact, usually return the user with the energy stored in elastic elements which are deformed during passive motions.
- INTEGRATION: a sure way to increase efficiency of the worker wearing the exoskeleton is to make it an active part of the production. Making it capable of collecting information useful for the workflow, and of actively interacting with the other entities involved (such as cobots) can be a powerful trojan horse for wearable robotics in SMEs. Obviously, this does not mean that the labourer who does not wear the exoskeleton is prevented to perform a human-robot interaction task, but only that wearing it must make the operation simpler, faster, and more efficient.

The RUs will assess all the advancements necessary for the achievement of the objectives. The project is expected to deliver a TLR of at least 4, obtained through validation in lab environment. Focusing to such ambitious aim, the RUs will focus on four activities:

- **hybrid architecture mechanism design**: an innovative rigid-soft exoskeleton structure will be developed with the aim of collecting the advantages of both the rigid and soft exoskeletons while overcoming their limitations:
  - RANGE OF MOTION: the device must not constrain any upper-limb motion, in addition it must guarantee a workspace as similar as possible to that of the upper-limb without the exoskeleton.
  - JOINT ALIGNMENT: the proper alignment between the exoskeleton and the anatomical joints of the wearer must be guaranteed to avoid undesired reaction forces and torques at the human-robot interfaces.

  - FORCE TRANSMISSION: the device must transmit the actuation power to adequately support the user's degrees of freedom (DOFs) involved in the load-bearing phases, while being kinematically and dynamically transparent along the other DOFs.

- **human-robot interaction (HRI) control design**: a set of control strategies will be designed to enable safe and efficient interactions between the exoskeleton, its wearer and the collaborative robots in the environment. The main features of the HRI control can be summarized as follows:

  - TRANSPARENCY/READYNESS: the control strategy will guarantee a prompt reply to the user intention of movement while providing a desired level of assistance in the load lifting/holding/moving tasks.
  - ADAPTIVITY: the level of assistance provided by the exoskeleton will be dynamically adapted according to the user's task. Different kinematic and dynamic patterns will lead to different parametrizations of the device controller to better fit the task requirements during its evolution.
  - SAFETY: the control design will consider all the aspects linked to the safety of the exoskeleton wearer.

- **design of an innovative actuation paradigm**: an innovative actuation architecture aimed at the worker's performance enhancement will be developed with three goals:

  - WEIGHT: the actuator weight has to be limited, both to avoid perceived discomfort and to limit joint inertia.
  - COMPLIANCE: the actuation system must be characterized by a certain compliance, so to mimic the biomechanical behaviour of the human body and to permit back-drivability and impact force tolerance.
  - CONSISTENCY: the actuator has to be able to generate the joint torque not only at the required intensity, but also with the necessary speed and with a frequency response adequate to the dynamic behaviour of the exoskeleton in motion. Last requirements are related to the ease of assembly, low components cost, energy-saving and sustainability.

- **mechatronic design and system integration**: the mechatronic layout of the exoskeleton will be conceived at both hardware and software levels to collect and share data with the work environment. The design activity will come out with precise guidelines which will affect both the design of the exoskeleton and the implementation in its work environment:

  - SENSING: definition of sensors (proprio- and extero-ceptive) needed for an effective integration.
  - DATA EXTRAPOLATION: design of the electronic and software interface necessary for collection, processing and transmission of data towards the integrated work environment.
  - INTERFACING: development of a collaborative platform able to interpret information coming from the device and oriented at enhancing process efficiency

(by optimized HRI strategies) and user safety (by localizing and tracing the worker's position and posture).

5 Conclusions

In conclusion, the project will deliver theoretical results and novel tools which will contribute to the advancement of knowledge in all the four main topics. In particular, it will contribute to the development of a comprehensive musculoskeletal model for the upper-limbs including the effect of shoulder girdle movement. A new comfortable kinematic structure for the exoskeleton will be developed, allowing for the user's natural joint ROM, thanks to a highly kinematic redundancy. The theoretical and experimental investigations that will be carried out for the design of the flexible couplings could be the starting point for the development of hybrid-architecture exoskeletons supporting other body parts or with different purposes.

eXoft will develop a new controller based on adaptive intelligent algorithms that can be personalized to the user's physiology and muscles assistance requirements that change with the tasks. The control framework will be capable of partly offloading the human biomechanics from the required effort yet maintaining a certain level of hardware transparency and freedom of motion for the user, thus, it will contribute to the improvement of the wearer's ergonomics.

Mode of actuation and power transmission are one of the challenges in the research and development of upper-limb active exoskeletons. Currently, the 97% of upper-limb exoskeletons are conventionally actuated (electrically, pneumatically, hydraulically), while there are only few examples of hybrid actuation. This research wants to contribute to the field by proposing an actuation paradigm that is specifically conceived for the application and meets the requirements in an original way.

The integration of a wearable device in a productive scenario requires the definition of several communication protocols, as well as the deep knowledge of its impact on the whole system safety. Such aspects, in the light of the interest aroused by collaborative human-centric industrial layouts, is for sure a field worth of investigation. While developing the related technical issues, the project will introduce innovation in all its key aspects. The use of the exoskeleton will introduce an innovative HRI opportunity with the consequent advancements in the techniques of close collaboration among humans and machines.

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